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Abstract

The excitation energy sharing between the two partners of binary dissipative collisions was derived for the ^{40}Ar + ^{nat}Ag system at 27 and 44 MeV/u. From the eventual equilibration of energy between the two partners, and their separation time obtained from Landau-Vlasov simulations, the energy relaxation time was extracted, and compared with theoretical predictions.

The knowledge of the different time scales involved in nuclear collisions is of crucial importance at energies above the Fermi energy. In this domain the reaction times become very short, possibly of the order of the energy relaxation time; it therefore becomes difficult to clearly distinguish between a collision stage and a deexcitation stage. For binary dissipative collisions, the interaction time extends up to the re-separation of the two partners. When studying the deexcitation of these fragments, it is generally assumed that they have reached thermal equilibrium. A review of the different time scales involved in nuclear collisions can be found in [1]. In binary dissipative collisions one can experimentally derive the excitation energy sharing between the two primary partners. If both have the same excitation energy per nucleon (i.e. the same temperature), then one may assume that the dinuclear system was equilibrated at re-separation; the associated time has to be derived from a dynamical simulation of nuclear collisions. First data using this method were published in [2]. They were obtained from the reactions of ^{40}Ar on ^{nat}Ag at 27 MeV/u . In this note we report on the same system at 44 MeV/u comparing the energy relaxation times thus obtained with theoretical calculations.

The experimental method is based on exclusive measurements, detecting in coincidence the two final partners of the collisions. Experimental details can be found in [3, 4]. The emission angle (with respect to the beam direction) of the light fragment,θ_L, was taken as a reference, then at each corresponding value average kinematic quantities related to both fragments were measured (velocities of the

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light and heavy fragments, V_L, V_H, angle of the heavy fragment, θ_H). The method used to derive these quantities is described in [5], and the results in [6]. These data suggest the presence of an abundant prequilibrium emission, which it was difficult to separate, experimentally, from emission by the light fragment. Therefore the contribution of preequilibrium particles (in mass A_{PE} and energy E_{PE}) was taken from Landau-Vlasov dynamical simulations, which were shown in [6]to correctly describe the dynamics of the peripheral and semi-central collisions. Then the primary masses of the light partners of the collision are calculated from the dynamics following:

$$\begin{aligned} A_L^{'} &= \frac{A_{TOT} - A_{PE}}{\sin \theta_L} \times \\ &\left(\frac{< V_L >}{\sin < \theta_H >} + \frac{< V_H >}{\sin \theta_L} \right)^{-1} < V_H > \end{aligned} \tag{1}$$

The subscripts L (H) refer to the light (heavy) partner of the collision, and the prime(′) stands for the primary light fragment; A_{TOT} is the sum of the projectile and target masses. Equation (1) just expresses the conservation of perpendicular linear momentum. The primary mass of the heavy partner follows from total mass conservation. The ratio of the excitation energy of the light fragment to the total excitation energy is taken equal to the ratio of the mass loss of this fragment (primary - measured) to the total mass loss. The calculation was performed at two different angles and for different final Z values of the light fragment. In Fig 1 the excitation energy ratios are plotted as a function of the detected atomic number of the light fragment; for completeness, the data previously obtained at 27 MeV/u are also displayed in Fig 1. The errors bars come mainly from uncertainties in determining the most probable velocity ($< V_H >$) and angle ($< \theta_H >$) of the heavy partner.

Solid lines in the figure indicate the expected behaviour assuming equal temperatures. It can be concluded from this figure that the equilibrium between the two partners of the collision is far from being reached at 15° at 27 MeV/u but is achieved in the three others cases. This clearly fixes upper limits for the energy equilibration time, namely the re-separation time between the two fragments, which can be derived from the dynamical simulations [6]. This needs a link between the experiment and the calculation, which can be done through the emission angle of the light fragment recalling the strong correlation between this angle and the impact parameter. Results are given in table 1, which restrict the energy relaxation time to the range 100-180 fm/c ($\leq$125 fm/c) for an incident energy of 27 (44) MeV/u .

Theoretical calculations of the energy relaxation time have been performed for many years. Calculations in infinite nuclear matter predict that this time decreases by a factor of 5 when the incident energy increases from 20 to 100 MeV/u [7, 8, 9]. In these papers the relaxation is assumed to be essentially due to nucleon-nucleon collisions, and the large variations observed from one calculation to another [1]are due to the different values adopted for the nucleon-nucleon cross section. For finite nuclei, the relaxation time has to be derived from dynamical simulations, and it

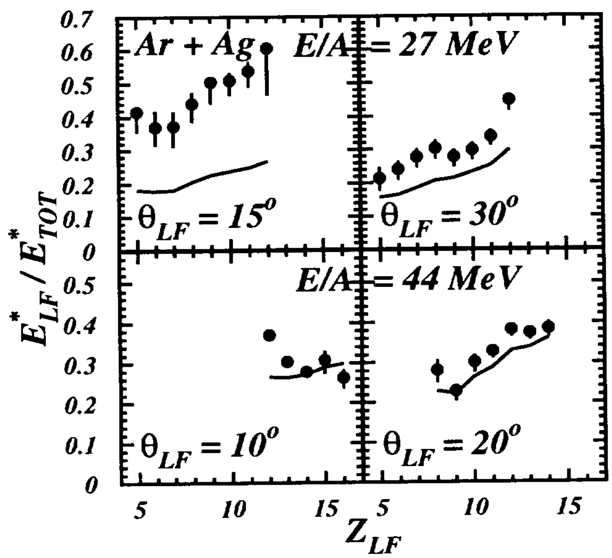

Figure 1: *Ratio of the excitation energy of the light partner to the total excitation energy for different atomic numbers of the detected light fragment. Data were obtained at two incident energies, and at two detection angles of the light fragment at each energy*

E_{inc} (MeV/u)	θ_{LF}	b (fm)	t_{sep} (fm/c)
27	15°	8	100
27	30°	6	180
44	10°	5	125
44	20°	3	125

Table 1:

is generally related to the variation of the total quadrupole momentum, which decreases exponentially with time ($Q_2(t) = Q_2(t=0)exp(-t/\tau_Q)$). For a light system such as Ca+Ca, and the model of Cassing [9], the value of τ is $\sim$10 fm/c and is found to be independent of the bombarging energy. For the ^{40}Ar + ^{nat}Ag system and the Landau-Vlasov simulations of [6], a higher value of τ_Q is obtained, slightly decreasing when the incident energy increases, from 28 fm/c at 27 MeV/u to 18-20 fm/c at 44 and 57 MeV/u . Moreover in this framework the relaxation time was also found to be independent of the total mass of the system, as similar τ_Q values were found for the Ar+Al [10]and Gd+U [11]systems, both studied at 35 MeV/u . In ref [12], the authors of the Landau-Vlasov simulation define a local equilibrium time, related to the relaxation of the Fermi bisphere, which is 25% lower than τ_Q, but has the same behaviour as a function of the incident energy.

Full equilibration of energy should be reached around t ~3-4 times τ_Q, i.e. 100 fm/c for Ar+Ag reactions. In this sense, and relying consistently on the Landau-Vlasov simulations to derive both the re-separation time and the equilibration time, the ''experimental" energy relaxation times derived from table 1 are in good agreement (within 25%) with the calculated values.

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